EXPERIMENTAL TEST OF LOCAL OSCILLATOR–INDUCED PERFORMANCE LIMITATION FOR PULSE–MODE PASSIVE FREQUENCY STANDARDS*

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Abstract

An experimental test of Local-Oscillator (L.O.) degradation of time–sequential passive oscillator performance was accomplished using the TAC-controlled crystal oscillator described in an accompanying paper. For this quantitative demonstration, an electronic frequency–counter discriminator replaced the trapped ion physics package in a closed–loop experiment. With a 10 second cycle time and 5 second dead time, L.O. limited stability was demonstrated in excellent agreement with theoretical calculations. The results are also in agreement with computer simulations and confirm previous noise analysis for the case of a passive standard with short pulse "Ramsey" interrogation.

Background

A methodology for calculating L.O. induced degradation for pulse-mode atomic frequency standards has been available for some time, representing the first quantitative analysis of this fundamental limitation for any passive atomic frequency standard.[1,2] Passive standards use atomic or ionic transitions with very narrow linewidths to sense and correct the frequency of an ancillary local oscillator. Frequency variability in the L.O. is detected and corrected by counting photon or atoms. Statistical variation of these counts gives rise to a frequency stability (Allan Deviation of fractional frequency $\sigma_y(\tau)$) that improves with increasing measuring time τ as $\sigma_y(\tau) \propto 1/\sqrt{\tau}$. An ideal feedback loop might be expected to show a rapidly improving deviation $\sigma(\tau) \propto 1/\tau$ as it transitions between L.O. performance at shorter measuring times to statistical atomic performance at longer times.

The importance of the L.O. analysis is that it shows that any time-variation in the sensitivity of the feedback signal will alias (down-convert) relatively high–frequency oscillator noise to near zero frequency. The associated $\sigma(\tau) \propto 1/\sqrt{\tau}$ L.O. contribution fundamentally limits and masks the white frequency noise performance of atomic standard itself.

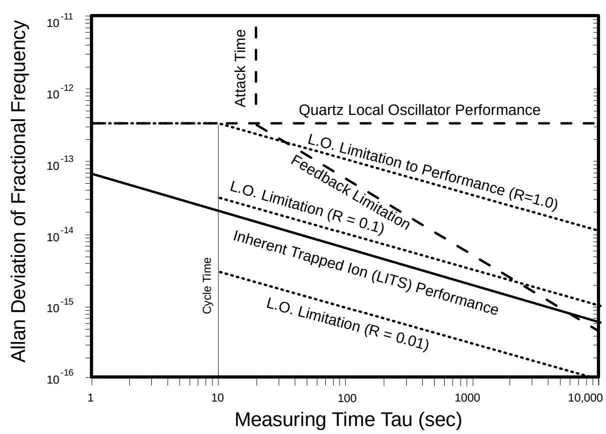

Figure 1: Short– and medium–term frequency stability features for an ion trap standard with cycle time of 10 seconds. Values for **R** are shown in Fig. 2.

The interrelation of these various dependencies is shown in Figure 1 for the JPL mercury–based Linear Ion Trap Standard (LITS) stabilizing a quartz L.O.

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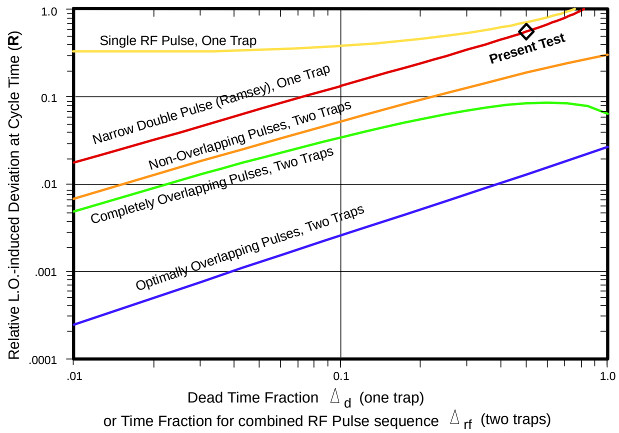

Figure 2: Calculated dependence of dimensionless constant **R** on "dead time" for various interrogation strategies assuming a Flicker–Frequency L.O. **R** describes the L.O.–limited $\sigma \propto \tau^{-}$ deviation for the passive standard (see Fig. 1). A value of $\mathbf{R} = 0.533$ is predicted for the present experiment, corresponding to a dead time fraction of 0.5 and narrow double pulse interrogation.

with an assumed flicker–frequency floor of 3×10^{-13}. The L.O.–induced stability limitation is described in terms of a dimensionless constant **R** which depends on the details of the interrogation strategy, e.g. dead time and rf pulse length. Calculated values for **R** vary from 0.2 to 1.0 for typical interrogation strategies. From Fig. 1 we can see that the performance of this standard will be substantially degraded for these strategies, unless an improved local oscillator can be found.

The top two curves in Figure 2 show the calculated dependence of **R** on "dead time" for single- and double–pulse interrogation for a flicker–frequency L.O.[2] The advantages of a short dead time and of Ramsey interrogation are apparent. For example, if the fractional dead time is only 0.1, **R** is reduced to a value 0.135. This compares to an absolute minimum of $\mathbf{R} = 0.31$ for single–pulse interrogation. Also shown are curves that display the much lower values for **R** which are available if dead time is eliminated by the use of two independently interrogated ion collections.

In this paper we consider the particularly simple case of a repeating interrogation cycle which has a constant sensitivity to L.O. frequency for a period of time, followed by an equal "dead–time" during which the frequency of the L.O. is not observed. This case is approximated in atomic standards by "Ramsey

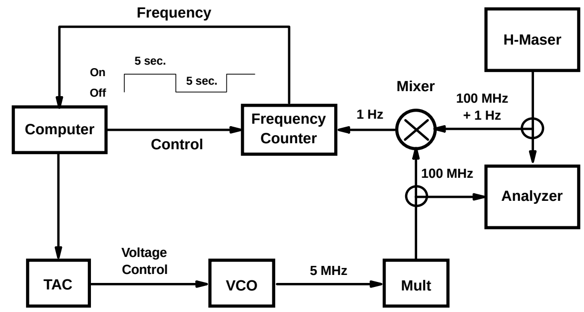

Figure 3: Schematic Diagram showing Feedback Loop and Analyzer

Interrogation" with very short interrogation pulses, and was one of those previously analyzed.

Experimental

Figure 3 shows the feedback loop for the tests described here. A high resolution electronic frequency counter replaces the trapped–ion physics package in order to eliminate the effects of discriminator–induced noise, and thus to isolate those instabilities that are due to the local oscillator and the feedback loop. The tests focused on measurements with a relative large dead time fraction of 0.5. This enables a relatively quick transition from $\sigma(\tau) \propto 1/\tau$ feedback–limited performance to the $\sigma(\tau) \propto 1/\sqrt{\tau}$ L.O.–limited performance. The arrangement has no expected $1/\sqrt{\tau}$ contribution due to the H–maser reference, and so all such effects can be attributed to the L.O. and loop effects.

In addition to experimental tests, computer simulations were performed using a commercial software package with sequences of 16384 to 65536 noise events. Flicker noise was generated using the internal ifft, random noise, and cumulative normal distribution functions with a $1/\sqrt{\omega}$ fourier amplitude multiplying factor. The resulting simulated time sequences gave excellent (nearly constant) Allan Deviation performance for τ values less than one half the total sample size. Another test of this very simple and accessible simulation technique gave fairly good values for the logarithmic correction to an expected t^2 dependence of the time error variance, extrapolated from the beginning interval.[4]

Several different digital feedback loop algorithms

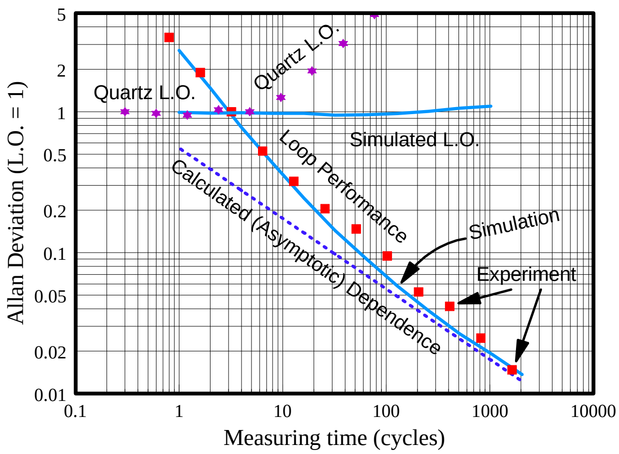

Figure 4: Calculated, simulated and measured loop performance for 50% dead time. Actual quartz oscillator stability was $1.9{\times}10^{-13}$ at 10 seconds (one cycle).

were tried, both in simulation and test. These included the lamp drift–rejecting 1–2–1 weighted loop algorithm often used for ion trap feedback systems[3], more conventional digital loops[5] and a new "white–walk" routine based on linear combinations of loops optimized for white and random walk noise.[6]

Results

Theoretical, simulation, and experimental data for Allan Deviation of fractional frequency are shown in Figure 4. The straight line asymptotic dependence corresponds to the value of $\mathbf{R} = 0.533$ given by Fig. 2 for the test configuration. All show excellent agreement. Normalization of the experimental and theoretical results was made to the flicker–floor for the TAC–driven quartz oscillator of 1.9×10^{-13}. Loop parameters for both simulation and experimental results were identical, and were optimized for random-walk-of-frequency L.O. noise on account of quartz oscillator frequency wander at the longer measuring times.

The results in Fig. 1 demonstrate a loop attack time of approximately 2.7 times the cycle time. These results are substantially improved over those attainable with the more conventional 1–2–1 feedback scheme. As shown in Figure 5, simulation results without dead time effects show a long–term $1/\tau$ performance improvement by a factor of two. We find that more conventional loops also improve on the 1–2–1 loop, but only by a factor of $\approx \sqrt{2}$.[5] The simulations also show that improper loop characteristics may give rise to $1/\sqrt{\tau}$ contribution from the L.O., even without dead time, or other time variation for the loop gain.

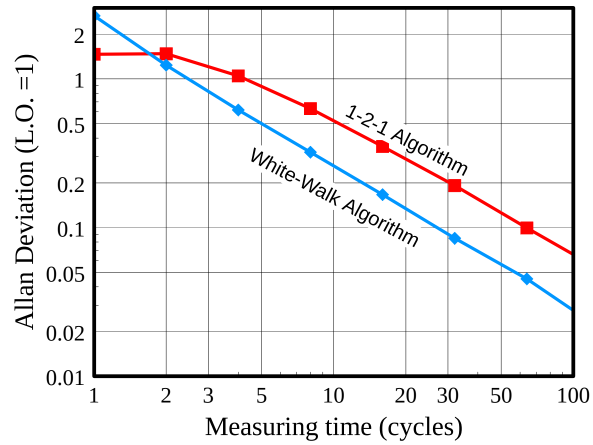

Figure 5: Simulated loop performance for several algorithms without dead time.

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